Interacting with Surfaces of Small Asteroids: Penetration Depth and Coefficient of Restitution

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Introduction: The dusty regolith covering the surfaces of asteroids and planetary satellites differs in size, shape, and composition from terrestrial soil particles and is subject to environmental conditions very different from those found on Earth. This regolith evolves in a low ambient pressure and low-gravity environment. Its response to low-velocity impacts, such as those that may accompany human and robotic exploration activities, may be completely different than what is encountered on Earth. Experimental studies of the response of planetary regolith in the relevant environmental conditions are thus necessary to facilitate future Solar System exploration activities.

Experimental Setup: We carried out a series of impact experiments into simulated planetary regolith in zero- and reduced-gravity conditions using two experimental setups and a range of microgravity platforms. The Physics of Regolith Impacts in Microgravity Experiment (PRIME) flew on-board the NASA KC-135 and C-9 airplanes for a total of 3 flight campaigns recording impacts into granular materials at speeds of ~4-230 cm/s. The COLLisions Into Dust Experiment (COLLIDE) is conceptually close to the PRIME setup. It flew both on the Space Shuttle in 1999-2001 and more recently on the Blue Origin New Shepard rocket in 2016, recording impacts into simulated regolith at speeds between 10 and 120 cm/s. For the analysis presented here, we used PRIME-3 and COLLIDE data.

Both PRIME and COLLIDE setups consist in a target tray containing regolith simulant grains and a spring-loaded mechanism to launch a cm-sized projectile into this target (Figure 1). A camera was used to record the impacts in the individual chambers. For PRIME-3, individual experiment boxes could be free-floated.

Coefficient of Restitution: A number of impacts during the COLLIDE-1, -3, and PRIME-3 campaigns showed a rebound of the projectile after impact on the target and allowed for the measurement of a coefficient of restition $\varepsilon = v_f/v_i$, v_i and v_f being the projectile velocities before (initial) and after (final) the impact. For speeds above 30~cm/s, impacts systematically produced an ejecta blanket and coefficients of restitution of the projectile could either not be measured or were of the order of 10^{-2}.

At impact speeds between about 20 and 30~cm/s, both ejecta production and projectile rebound without ejecta were observed. Below 20~cm/s, only rebounds without ejecta were observed. In order to compare our results to the experimental work performed in 1g, we fit a power law to this set of data. The index we obtain with our data is -0.27, similar to the value of -1/4 found in 1g. This overall index value is twice as high as expected from the theory of an elastic sphere impacting a plane surface and indicates that energy absorption in a bed of granular material is not entirely captured by the mechanics of elastic surfaces.

Projectile Penetration Depth: In the PRIME-3 video data, the resolution is high enough to determine the maximum penetration depth of the projectile into the target. We do not observe any correlation between the maximum penetration depth (z_{max}) and the equivalent total drop distance (H). This is in contrast with the relation $z_{max} \sim H^{-1/3}$ observed in 1g, representative of a scaling by impact energy. A scaling by momentum was not successful either. Instead, we will show that it is possible to scale the penetration depth with the quantity $\mu^{-1}(\rho_p/\rho_g)^{0.1}D_p^{2/3} H^{1/3}$, with μ the coefficient of friction of the target material, ρ the density of the target (g) and projectile (p), and D_p the projectile diameter.

Conclusion: During the PRIME and COLLIDE experiment campaigns, we observed projectile rebound off the target in microgravity ($<10^{-4}g$). None of the impacts in 1g and reduced gravity (0.05g) displayed a similar behavior. The maximum penetration depth of the projectile into the target in reduced and microgravity was observed to depend more on the projectile size and energy and less on its density difference with the target than in 1g. These experiments show that the ambient gravity has a significant influence on the behavior of layers of granular material.
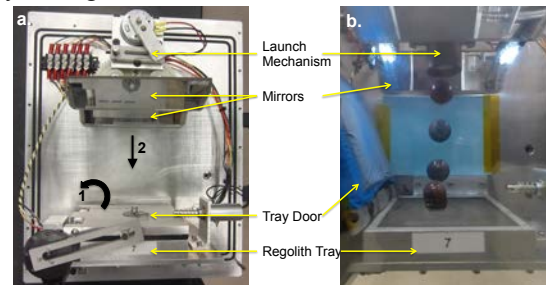

Figure 1: PRIME-3 hardware inside the vacuum box. (a) Before the experiment runs, regolith is stored in the regolith tray that opens (1) to allow for the launched marble (2) to impact. The launch mechanism consists of a spring whose constant determines the launch velocity. (b) This montage of 7 frames of a marble impact and rebound off a JSC-1 bed. The marble speed is much reduced after impact.